COMPARISON OF MEASURED AND CALCULATED SOUND VELOCITY NEAR THE SEA SURFACE.

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NAVAL POSTGRADUATE SCHOOL
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THESIS

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by

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ABSTRACT

Measured values of sound velocity in sea water are compared to sound velocity calculated by several empirical relations. Among the empirical relations examined are Wilson's October, 1960 equation and Frye and Pugh's 1971 equation. Results indicate that all empirical relations have their maximum differences in the first 20 feet of sea water. The difference measured is dependent on wind induced turbulence. Of the empirical relations examined, the Frye and Pugh equation provides the most accurate results.

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I. INTRODUCTION

This thesis is part of a joint experiment conducted by members of the Departments of Oceanography and of Physics and Chemistry at the Naval Postgraduate School. The objective, in general, was to measure as many significant physical parameters as possible of the near-surface environment and determine their interrelationships. The parameters measured were

1) Wave height
2) Water particle motion
3) Temperature microstructure
4) Sound Velocity
5) Salinity
6) Acoustic Amplitude Modulation
7) Acoustic Phase Modulation

This thesis focuses on the speed of sound in sea water and its deviations from what is referred to as a standard speed of sound as calculated by one of several empirical equations. Salinity and temperature will be the primary parameters considered affecting the speed of sound in sea water although other factors are considered. However, it is upon temperature and salinity which the empirical formulae are based.

Wilson's October 1960 equation [1] has a standard deviation error of 0.3 m/sec. due simply to the fact that it is a least-square fit to data obtained in a laboratory using filtered sea water. Such conditions are necessarily ideal. Within the present state of technology, it is possible to measure the speed of sound in sea water under field conditions to within 0.1 m/sec. [2]. In view of the wide use of Wilson's equation by the Navy, and by investigators of sound propagation modes, it would

be desirable to know how this empirical relation stands up under field conditions. One objective is to compare results given by Wilson's equation with actual values measured in the field to determine what accuracy one might reasonably expect of it in the field.

Several other equations were examined in addition to Wilson's October, 1960 equation for purposes of comparison. They are

1) Frye and Pugh's Equation [3],
2) Del Grosso's 1952 Equation [4],
3) Wilson's June, 1960 Equation [5].

Differences between measured and calculated sound velocity using these equations are examined and results compared with differences obtained using Wilson's October equation. The purpose of such a comparison is to determine if a more precise prediction of sound speed in sea water can be made. Particular attention is given to that portion of the experiment where there is sharp contrast in sound velocity differences. The reason for this interest is to look for changes in environmental conditions which are not accounted for in laboratory-derived empirical relations. Failure to include environmental factors other than the classical ones of temperature, salinity and depth may be the cause for large differences from a standard speed of sound.

The differences in question are not great, but do approach a value of almost a meter per second. In the anti-submarine warfare problem such an error has not been particularly important in the past. However, as detection ranges increase with more powerful sonars, the importance of understanding environmental conditions to obtain more precise range data increases. This is particularly true if weapons are fired either

remotely from a helicopter or fired as a missile at ranges of 20,000 yards and more. An error of 1 meter per second in sound velocity in the upper layers can produce an error in range on the order of several hundreds of yards, possibly, putting a target outside a weapon's acquisition range.

II. GENERAL

The velocity of sound can be expressed by the hydrodynamic formula

$$c = \sqrt{\frac{r}{\rho\beta}}$$

where c = velocity

r = ratio of the specific heats

ρ = mean density

β = the coefficient of isothermal compressibility

The British Naval authorities used this formula prior to WW II to manufacture tables and nomograms for use by their Navy. The same formula was also used in the 1930's and 1940's by the oceanographer S. Kuwahara [6] for computing the tables of the Japanese Navy and by K. Kalle [7] in preparing nomograms with parallel scales for use by the German Navy. Not to be outdone by its opponents, the Naval Research Laboratory of Washington, D. C. employed the formula compiling tables for the U.S. Navy [8], and last, but not least the U.S.S.R. utilized it for compiling their own tables. Opposing sides in WW II were in effect all using the same basic formula in their calculations of sound speed in water as they went about their daily routine of conducting submarine and anti-submarine warfare against one another.

However, as technology advanced in the instrumentation for measuring sound velocity in sea water during the 1950's it became apparent that the figures obtained with the aid of tables and nomograms, based on theoretical formulae, fell below the true figures by an average of 3-4 m/sec. [4]. Greenspan and Tschiegg [9] used a direct method in 1956 for measuring the speed of sound in pure water. They used quartz oscillators, and a cylindrical tank with a plane transducer at each end. The time of flight

of a pulse of sound was determined from a measurement of pulse repetition frequency required to set the successive echoes into time coincidence. These results were adopted by the National Bureau of Standards and are used widely by manufacturers in calibrating velocimeters. Del Grosso [10] made measurements with an ultrasonic interferometer at a frequency of 5 MHz and reported in 1970 an observed error of about +0.34 m/sec. in Greenspan and Tschiegg values (also referred to as NBS values). The above error applies only to our area of interest which for this experiment is a temperature range of 11° C. to 20° C. Observed errors were reported by Del Grosso over a range of from 0° C. to 100° C.

The most recognized work in this area, however, seems to be that reported by Wilson which was published in June, 1960 [5] and modified in October, 1960 [1]. He produced his well-known empirical relation of temperature, salinity, and pressure which, at least under laboratory conditions, will give a speed of sound accurate to within 0.3 m/sec. Several investigators have since reworked Wilson's data and have proposed changes. One proposal was made by Lovett [11] to subtract 0.65 m/sec. from results obtained using the October equation. This proposal was based on observations that such a change would bring the Greenspan and Tschiegg results, as modified by Del Grosso, in agreement with the October equation. However, this thesis was unable to substantiate this proposal as will later be shown. Frye and Pugh offered a new equation in 1971 which contained only 11 terms as compared to Wilson's June equation with 20 terms and his October modification with 22 terms. They also claimed an estimated standard deviation of only 0.1 m/sec. Frye and Pugh based their equation on Wilson's June 1960 data, eliminating over two-thirds of this data as combinations that do not naturally occur. They claim to

have made a significant improvement over Wilson's October, 1960 equation, and to some extent this seems to hold true as will later be shown. There are several other equations derived by prominent people in the field for calculating sound velocity, and all are of about the same quality and all are based on Wilson's laboratory data or data obtained from experiments conducted by other investigators in the laboratory.

The best laboratory work seems to be the Greenspan and Tschiegg distilled-water equation (with Del Grosso's correction). This assumes that the speed of sound changes smoothly with temperature and that the sound speed derivative decreases monotonically as temperature increases [11]. The standard deviation is 0.025 m/sec. over a temperature range of 0^{o} C. to 100^{o} C.

The most accepted sea-water equation to exit the laboratory is Wilson's October, 1960 equation. For purposes of this thesis and for economy of time and space, only the following equations are restated. The Greenspan and Tscheigg equation as seen here does not include Del Grosso's correction. These corrections depend on the temperature range of interest.

In these equations the speed of sound, "C" is expressed in m/sec., "T" refers to temperature in degrees celsius, "P" refers to total pressure in kgm/cm^2, and "S" refers to salinity in parts per thousand ($^{o}/oo$). Notice that the Greenspan and Tschiegg distilled-water equation is a function of temperature only, but the other two involve the three parameters "T", "S" and "P" and include cross product terms.

Greenspan and Tschiegg equation [9]

$$C = 1402.736 + 5.03358T - 0.0579506T^2 + 3.31636 \times 10^{-4}T^3$$
$$- 1.45262 \times 10^{-6}T^4 + 3.0449 \times 10^{-9}T^5$$

Wilson's October, 1960 equation [1]

$$C = 1449.140 + V_T + V_P + V_S + V_{STP}$$

where

$$V_T = 4.5721T - 4.4532 \times 10^{-2}T^2 - 2.6045 \times 10^{-4}T^3 + 7.9851 \times 10^{-6}T^4$$

$$V_P = 1.60272 \times 10^{-1}P + 1.0268 \times 10^{-5}P^2 + 3.5216 \times 10^{-9}P^3$$
$$- 3.3603 \times 10^{-12}P^4$$

$$V_S = 1.39799(S - 35) + 1.69202 \times 10^{-3}(S - 35)^2$$

$$V_{STP} = (S - 35)(- 1.1244 \times 10^{-2}T + 7.7711 \times 10^{-7}T^2 + 7.7016 \times 10^{-5}P$$
$$- 1.2943 \times 10^{-7}P^2 + 3.1580 \times 10^{-8}PT + 1.5790 \times 10^{-9}PT^2)$$
$$+ P(- 1.8607 \times 10^{-4}T + 7.4812 \times 10^{-6}T^2 + 4.5283 \times 10^{-8}T^3)$$
$$+ P^2(- 2.5294 \times 10^{-7}T + 1.8563 \times 10^{-9}T^2)$$
$$+ P^3(- 1.9646 \times 10^{-10}T)$$

Frye and Pugh's equation [3]

$$C = 1449.30 + V_T + V_P + V_S + V_{TP} + V_{ST}$$

where

$$V_T = 4.587T - 5.356 \times 10^{-2}T^2 + 2.604 \times 10^{-4}T^3$$

$$V_P = 1.5848 \times 10^{-1}P + 1.572 \times 10^{-5}P^2 - 3.46 \times 10^{-12}P^4$$

$$V_S = 1.19(S - 35) + 9.6 \times 10^{-2}(S - 35)$$

$$V_{TP} = 1.354 \times 10^{-5}T^2P - 7.19 \times 10^{-2}TP^2$$

$$V_{ST} = 1.2 \times 10^{-2}(S - 35)T$$

III. EXPERIMENT SITE

The experiment was conducted at the Naval Undersea Center Oceanographic Tower near San Diego, California on 8 and 9 June, 1972. The tower is installed in a mean depth of water of 60 feet, approximately one mile off Mission Beach. It is constructed of steel and concrete and permanently embedded in the sea floor. There are several levels on this 40 foot square tower. The lowest level being primarily for gaining access, the next level up provides space for preparing instruments for placing in the sea, and the highest, which is mostly enclosed, is used for electrical monitoring, recording equipment and enough living space for personnel conducting experiments. The legs of the tower slope five degrees into the sea bed. Tracks are located on the north, south and west sides of the tower for lowering instruments attached to rail carriages into the sea to any depth down to the ocean floor. The western side was used for this particular experiment because of its exposure to the dominant swell.

All instruments with the exception of the Baylor Guage, for measuring wave height flucuations, were mounted on an aluminum pipe frame. The frame measured 6 ft. x 6 ft. and extended out from the inboard side a distance of 12 ft. (Figures 1 and 2). The Baylor Guage was suspended from a 15 ft. I beam and placed above the center of the 6 ft. aluminum frame.

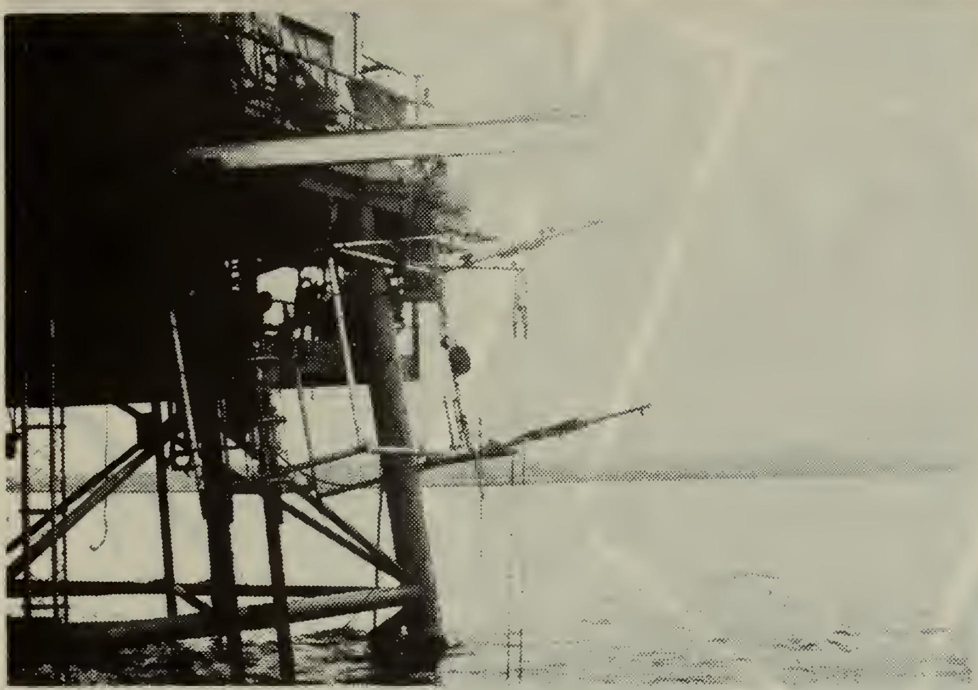


Figure 1: Tower and instrument frame

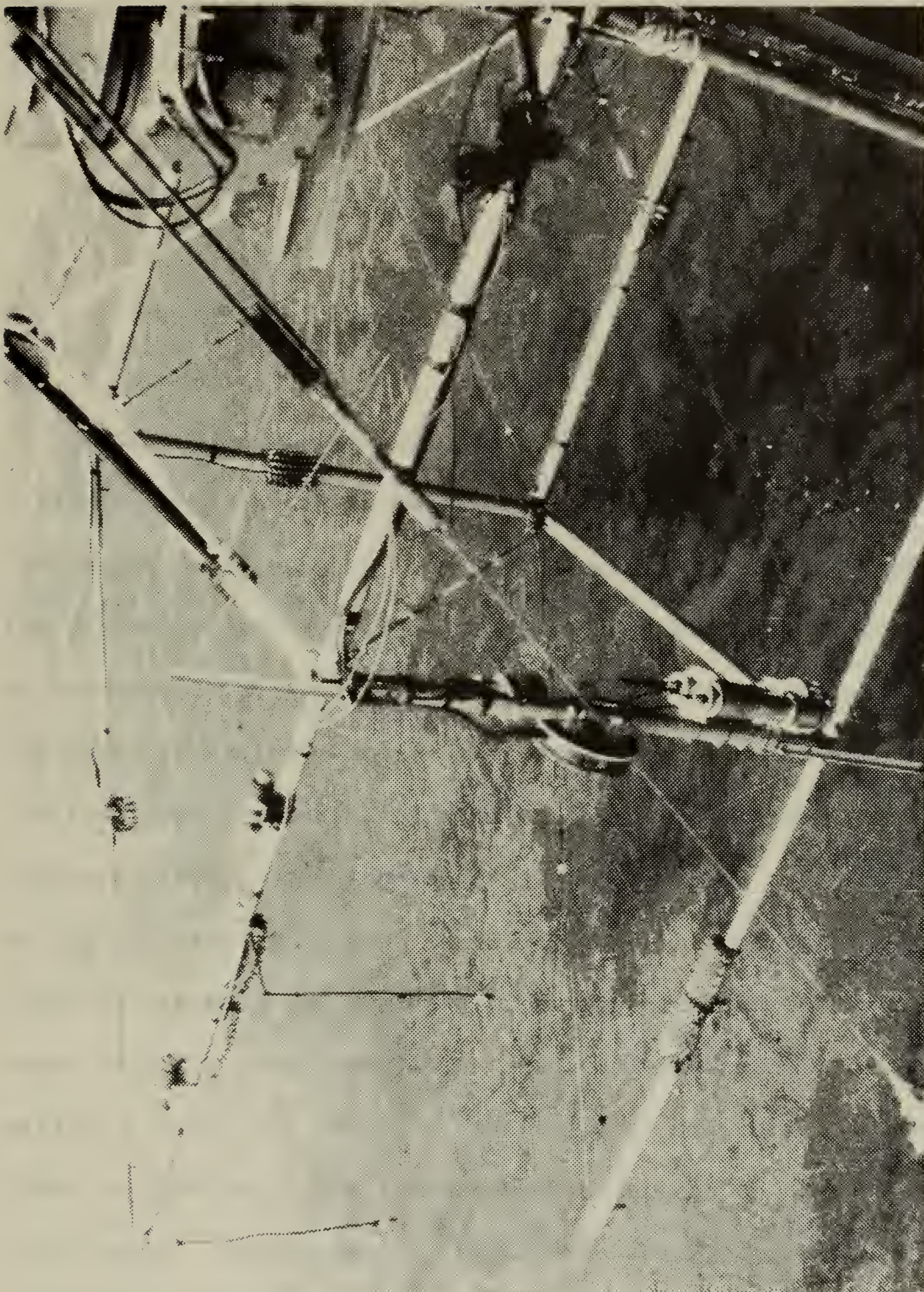


Figure 2 Instrument frame

IV. SENSORS

The sensors used in the experiment were chosen primarily on the basis of availability. The positioning of the sensors on the aluminum frame was based on the following three equal considerations:

a) avoidance of mutual interference

b) stability and integrity of the sensor and metal frame

c) free flow of mean current into the array of sensors

Sound velocity was measured with a Ramsay MK-1 Deep Sea Probe utilizing only the velocimeter and thermistor portion of the probe. The Ramsay velocimeter is a sing-around type transducer and transmitter, the prototype having been developed by Greenspan and Tschiegg in 1957. It transmits a pulse of 4 MHz into a twenty-five centimeter sound path. The pulse is reflected twice to reduce errors due to water motion. The received pulse then triggers the transmitter setting up a Pulse Repetition Frequency (PRF). This frequency is between 5600 and 6400 Hz depending on the velocity of sound. Sound velocity in meters per second can be found by dividing the PRF by 4. The PRF controls the output of the sound velocity oscillator. The output of the sound velocity oscillator will be 1/2 the PRF and twice the velocity of sound in meters per second (2800 to 3200 Hz). The frequency also depends on circuit delays and path length. Manufacturing limitations make it impossible to construct a known path length to the desired degree of accuracy. It is, therefore, necessary to calibrate in a liquid for which velocity of sound is known accurately such as distilled water. Ramsay Corporation performed initial calibration in November of 1971 using Greenspan and Tschiegg values for

sound velocity in distilled-water and an accuracy to 0.01 meters per second was determined. In May of 1972 a calibration check of the velocimeter used in this experiment was conducted at the Naval Postgraduate School's technical laboratory and an accuracy of 0.05 meters per second was observed. Ramsay's initial calibration was performed over a controlled temperature range of from 0 to 30° C. The check at the Naval Postgraduate School was only at temperatures in which we were expecting to operate, namely between 10° to 20° C.

The temperature used in the calculations were obtained from the thermistor probe on the Ramsay unit which is located at the center of the base of the probe just beneath the sing-around transducer and transmitter. The temperature sensor consists of the thermistor probe and the temperature oscillator, matched with a compensating network to provide desired frequency endpoints and band width. The frequency points are 5,000 Hz for 0° C. and 8,000 Hz for 30° C. and a linear relation for all points in between which provides a resolution of one Hz for 0.01° C. A check of this thermistor was also made in May of 1972 against a calibrated quartz thermistor and a high resolution mercury thermometer. An accuracy of 0.01° C. was observed.

The Ramsay probe was placed at the lower left hand corner of the frame (looking down) to take advantage of the support provided by the vertical and horizontal members of the frame as well as placing the sensor in close proximity to and in the same plane as the other thermistors and STD. This position was also well clear of the transducers and hydrophones used in measuring low frequency acoustic amplitude and phase flucuations.

The signals from the probe were transmitted via a sea cable to a deck unit. The deck unit used was a Ramsay Control unit Model 1B.

The Control unit discriminates the incoming frequencies into the bandwidth of temperature, sound velocity and pressure (pressure signal was not utilized because of the relatively shallow depth in which the experiments were conducted). The unit also amplifies the data signal, demultiplexes the FM telemetry tone signals, and converts these tone signals, to variable d.c. voltage. The operator has the choice of using either a voltage output or the frequency signal itself or both of the signals. The option used for purposes of this experiment was to record the frequencies and preserve the original signal while using the voltage signal to operate graphic recording equipment for monitoring equipment operation during the experiment.

Salinity was measured in-situ with a Bissett-Berman Model 9006 Salinity, Temperature and Depth Measuring System (STD). An inductively coupled sensor enables detection of conductivity, which is also compensated for temperature and pressure effects producing an output totally dependent upon salinity. The temperature sensor uses a platinum resistance thermometer. The output signal of conductivity and temperature shifts a PARLOC signal providing an FM analog of the two parameters. A deck unit is also used with this equipment similar to that described for the Ramsay probe. However, the d.c. voltage is in the 0 - 10 millivolt range. Frequencies were recorded for the same reasons that the Ramsay probe signals were recorded. Accuracy of the STD is ±.03 ppt. for salinity and ±.02^{o} C. for temperature. The STD was mounted on the inboard side of the aluminum frame and secured directly to the carriage. This was necessary because of both the size and weight of the STD.

Mounted in this position removed the STD from interferring with the other instruments and because of the direction of the predominate swell did not significantly hinder current flow around the sensory portion.

The sea surface elevation was measured with a Baylor Co. wave staff system Model 13528R with an accuracy of 1%. Particle velocity was measured with an Engineering Physics Company water current meter Model EMCM-3B. Both of these devices, the STD, and hydrophones for measuring phase and amplitude modulations are described in other theses by Frigge [12], Fitzgerald [13], Alexander [14], Krapohl [15]. This particular thesis is concerned primarily with the parameters measured with the Ramsay probe and the Bissett-Berman STD in order to make the comparisons with empirical equations as previously discussed.

V. EXPERIMENT PROCEDURE

Data from the instruments described in the previous section were recorded on a Sangamo Model 3562 fourteen channel FM tape recorder, with the exception of the phase and amplitude modulation signals which were recorded on separate equipment. A total of ten runs or recording periods were made on 8 and 9 June, 1972. Each run was of approximately 20 minutes duration which was considered necessary to insure an adequate sample for statistical analysis and for calculating and using average values. Depth and time for each run were determined by several factors; first, the objective of measuring the parameters as function of depth; second, the dependence of the parameters on the thermal structure of the water column as determined by a bathythermograph, and third, the variation of the parameters with the time of day. Due to both darkness and other scheduled commitments Run 7 was prematurely terminated which resulted in insufficient sample for analysis.

As a result of the above considerations depths of runs varied and are listed in Table I. Depths listed refer to mean water level from the surface to the bottom of the aluminum frame.

While each run was in progress environmental data were collected, both for purposes of making periodic checks on data being recorded and for correlating later. A Nansen cast was made during each run at the approximate depth of the instrument frame, and salinity determined with a standard induction salinometer. Table II contains environmental information.

Signals from the sensors were sent via cabling to the third level where an enclosed room was available for positioning both recording and monitoring equipment. Cables from the instruments were carefully led to

the top of the frame to avoid any possible interference of water flow around the sensing portions of the instruments. Just above the frame the cables were bundled and led to the top level of the tower and directly to their respective deck units. After processing of the incoming signals, such as in the case of the Ramsay probe where temperature and sound velocity frequencies were separated, the signals were recorded on strip charts and cabled to a master control panel. The strip chart recorders allowed continuous monitoring and provided a permanent record of the real time signals. The master control panel provided a relay to the assigned channel for each signal on the Sangamo tape recorder. It also provided the option of viewing the actual signal being sent to the tape recorder while simultaneously showing a playback of the signal just placed on the tape.

TABLE I

RUN	START Time (Local)	DEPTH (FT) (Bottom Frame)	LENGTH OF RECORD (MIN.)
		(8 JUNE)	
1	1405	18.74	25.0
2	1600	41.34	22.5
3	1654	34.84	33.5
4	1800	28.44	24.5
5	1830	21.80	19.0
6	1922	14.34	19.5
		(9 JUNE)	
8	0845	14.34	30.0
9	0935	47.26	20.0
10	1000	29.84	20.5

TABLE II

OBSERVED WEATHER						
RUN	TEMP (C^{o}) AIR	SURF	WIND DIR	WIND SPD (KTS)	CLOUD COVER (%)	SWELL DIR
1	19.7	19.2	240^{o}	8	100	W
2	19.6	18.95	250^{o}	10	100	WSW
3	19.2	18.20	240^{o}	9	100	WSW
4	18.7	19.1	225^{o}	6	100	SW
5	18.2	18.99	223^{o}	7	100	SW
6	17.9	18.77	235^{o}	4	100	SW
8	17.3	18.65	240^{o}	4	100	WSW
9	17.50	18.50	245^{o}	8	100	SW
10	18.8	18.5	240^{o}	4	60	SW

Runs 1 thru 6 conducted 8 June, 1972

Runs 8, 9, and 10 conducted 9 June, 1972

VI. DATA REDUCTION AND ANALYSIS

The recorded signals were played back and converted to voltages and a gain of ten applied through the COMCOR Ci 5000 analog computer. The voltage signals were then transcribed on to an eight track recti-linear Clevite strip chart recorder for a qualitative examination. Only six of the eight channels used contained signals of interest to the different investigators. Difficulty was experienced with the STD signals due to the low voltage output of the STD frequency to voltage deck unit and continuous problems with grounds interferring with other signals. It was, therefore, necessary to make separate strip chart recordings of the salinity signals.

A qualitative examination of strip chart records revealed that the greatest flucuations in sound velocity, temperature and salinity occured during Runs 1, 5, 6 and 8 which made them most suitable for digitizing. The runs which were not digitized had minimum flucuations, or short lived signals of interest, which because of their transient nature were not suitable for analysis due to lack of stationarity. Equipment problems were experienced with two other sensors not associated with the STD and Ramsay probe, which further made the digital value of Runs 2, 3, 4, 9 and 10 questionable.

Digitizing was accomplished by using a hybrid system consisting of a COMCOR Ci 5000 analog computer and a Xerox Data System Model 9300 digital computer. The analog signals were sampled at 5 times per second and read on to a seven track tape in octagonal base. Data from the seven track tape was then transferred by means of an IBM 360/67 computer to a nine track tape and converted to a hexadecimal base for use in analysis on the IBM 360 computer.

When digitizing, signals were amplified by a factor of ten in order to observe flucuations. This introduced calibration problems. A poteniometer was necessary to off-set large d.c. voltage levels from the amplification. Unfortunately the power supply was apparently not stable and drifts of as much as 0.1 volts were observed on the monitoring system. This contributes to errors in absolute values of:

Ramsay Sound Velocity	0.2 m/sec.
Ramsay Temperature	0.03° C.
STD Salinity	0.01 ‰

Therefore, in order to get absolute values of the parameters measured with the Ramsay and STD probe to the accuracy of the instruments it was necessary to take readings directly from the analog tape. Using available equipment, readings of Ramsay sound velocity and temperature, and STD salinity and temperature were taken from frequency counters averaged for 10 seconds with 20 second gaps between readings. This procedure was carried out for all Runs except Run 7.

These data provided the required in-puts to calculate sound velocity using Wilson's equation and the other empirical formulae discussed. When performing calculations for these equations, the pressure term used was based on an average sea water density of 1.025 grams/cm^3. This was converted to a constant of 0.1025 kg/3.28 cm^2ft. which when multiplied by depth in feet and added to atmosphere pressure of 1.0322 kg/cm^2 yields total pressure. The depths used were based on mean water level. The flucuations of actual depth caused by tides had an insignificant effect on the pressure term for the depths considered.

These calculated values of sound velocity were then subtracted from the Ramsay sound velocity to give a difference. These differences, in turn, were averaged for each of Runs 1 thru 10 with the exception of Run 7. The procedure of averaging was considered necessary in order to establish confidence in the accuracy of the absolute values of sound velocity from the Ramsay probe.

There was concern that the analog frequency data obtained above were introducing unacceptable errors in the average values due to the 20 second gap being to long. The relatively small errors in the temperature and salinity values on the digitized tape, previously indicated, have little effect on the calculated value of sound velocity. It was decided, therefore, to calculate sound velocity using digitized temperature and salinity with Wilson's October equation for Run 6. Data were averaged for 10 second periods every 10 seconds throughout the run. The only gap being two tenths of a second between each digital value. A total of 5600 digital points was used. The reason this was done for Run 6 was because it contained the largest flucuations of signals from the instrument probes. The size of error then between average sound velocity values based on digital data and that taken directly from the analog tape should be greatest on Run 6.

Graphs were made to compare the calculations. The number of averaged data points obtained from the digitized data is triple that obtained from the frequency data, and gives us a view of what was happening during the 20 second gap not covered by the frequency data. Agreement was very good. On the average for the entire record both were essentially the same as indicated by the small mean difference. The peaks and valleys missed in the 20 second gap are averaged out and have little effect on results.

Figure 3 shows sound velocity vs. time for Run 6 with one series derived from digital data and the other frequencies, both having been calculated with Wilson's October equation. The mean values are seen in Table III. These results permit us to look with increased confidence at absolute values of sound velocity obtained with frequency data recorded directly from the instruments. The errors in the digitizing process are bypassed successfully for average values. The digitized data, however, are still considered valid for statistical analysis.

Figures 4 thru 12 show variations of actual sound velocity and Wilson's sound velocity with time for the indicated runs. What is referred to as actual sound velocity is that measured with the Ramsay MK-1 calibrated to Greenspan and Tschiegg [9] distilled-water equation and corrected by Del Grosso's results [10]. The correction as discussed in section II of this thesis subtracts 0.34 m/sec. from Greenspan and Tschiegg's equation. The figures appear in order of increasing depth. A review of the runs on the 8th of June shows a relatively strong disagreement with Wilson's empirical formula near the surface, and as depth increases there is fairly good agreement in the vicinity of 0.3 m/sec. standard deviation envelope on Wilson's equation. The disagreement for all runs on 8 June is in the negative direction, that is, values of measured sound velocity are slower than predicted values. It is also observed that while the departure from Wilson's values decrease with depth it doesn't appear to be constant as evidenced by runs 4, 3, and 2. It seems a minimum difference is reached at run 4 and the difference begins increasing again with depth.

TABLE III

	NUMBER 10 SEC.AVG.PTS.	MEAN SOUND VELOCITY
Frequencies read direct from tape (10 sec. avg. of analog signal at 20 sec. intervals)	39	1512.26
Digitized data (10 sec. avg. of digitized data every 10 sec. - no interval - each 10 sec. is an avg. of 50 values)	112	1512.28

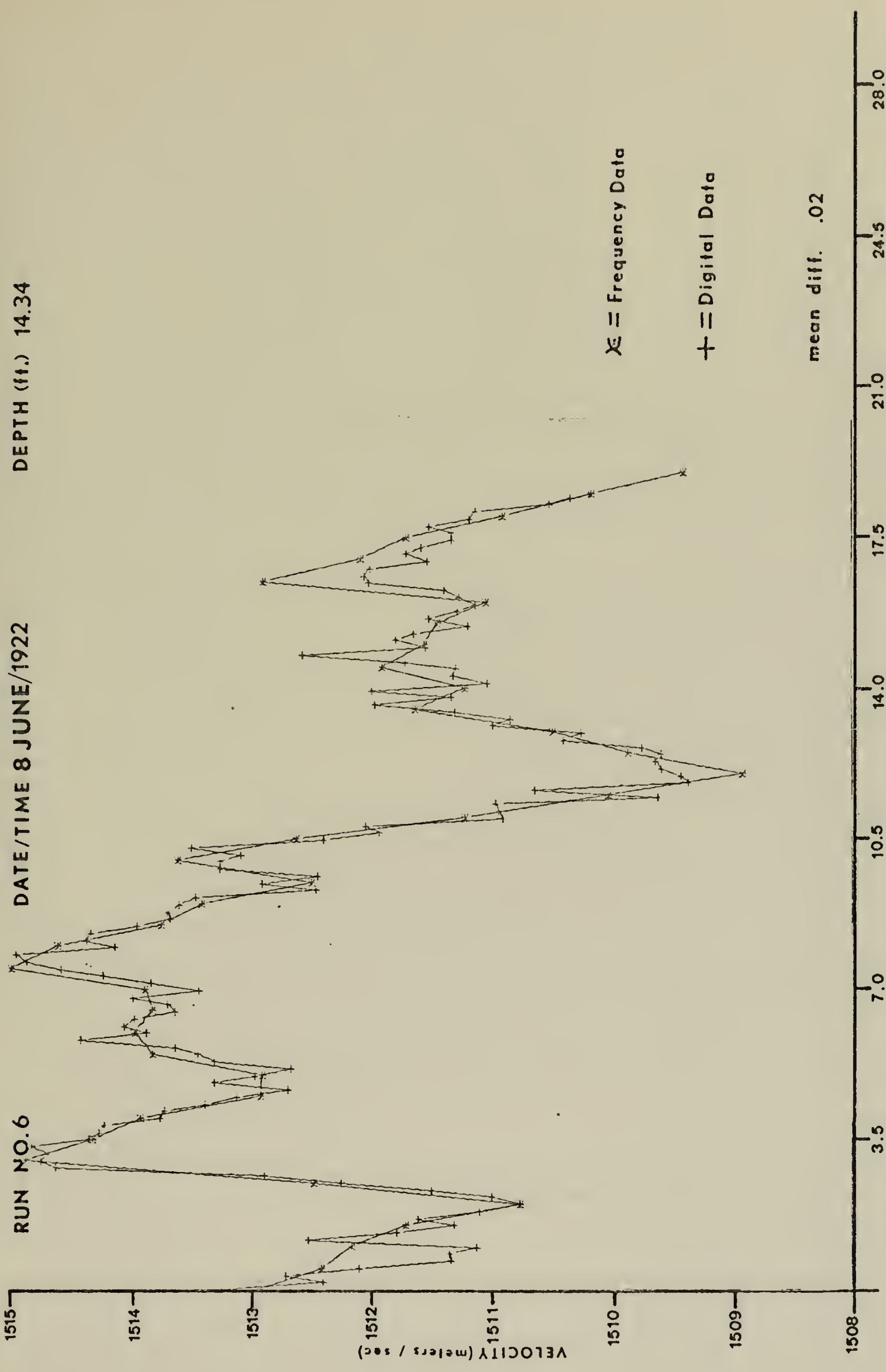
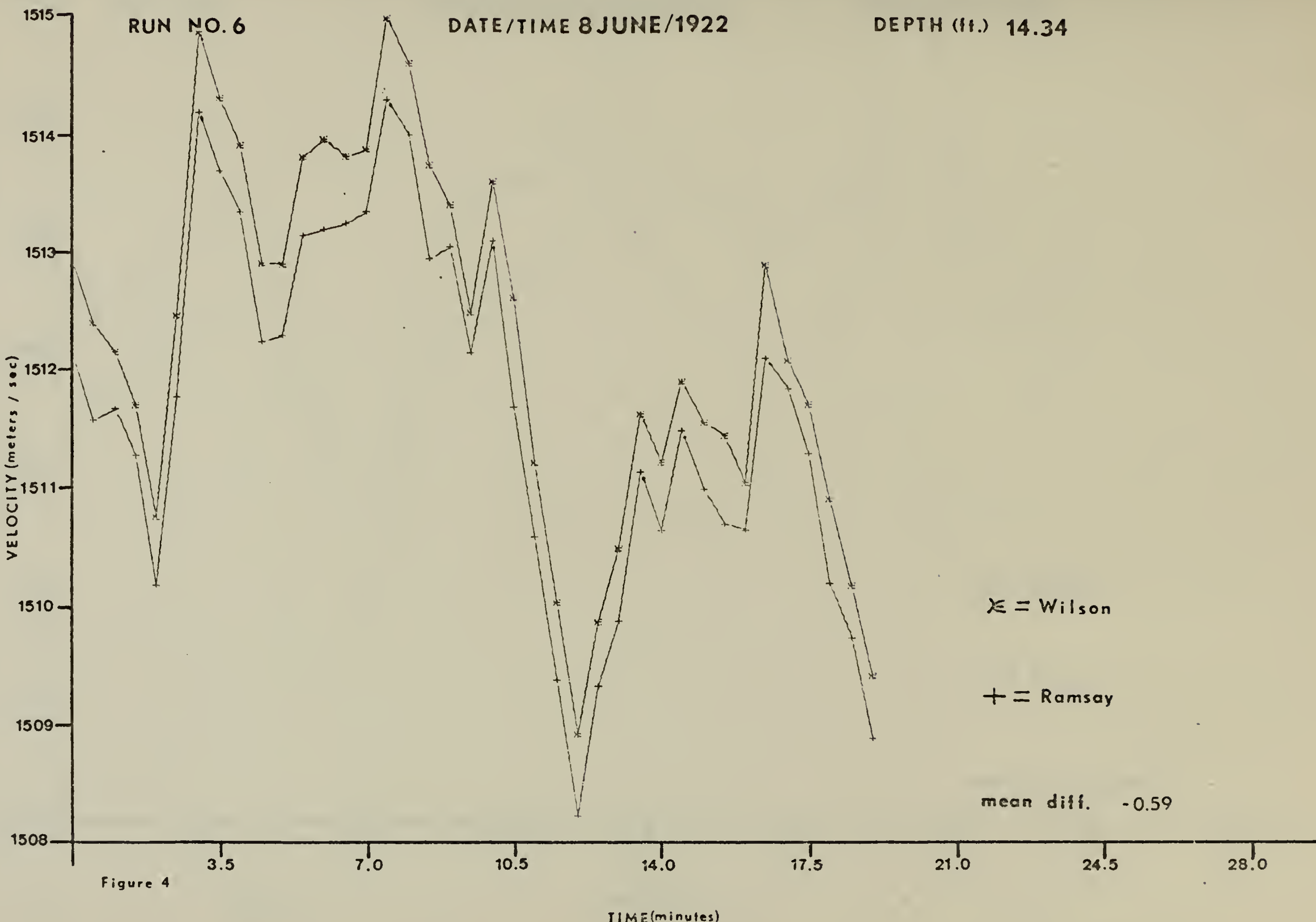

RUN NO.6
DATE/TIME 8 JUNE/1922
DEPTH (ft.) 14.34
X = Frequency Data
+ = Digital Data
mean diff. .02
VELOCITY (meters / sec)
1515
1514
1513
1512
1511
1510
1509
1508
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)

Figure 3



RUN NO. 6
DATE/TIME 8 JUNE/1922
DEPTH (ft.) 14.34
1515
1514
1513
1512
1511
1510
1509
1508
VELOCITY (meters / sec)
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)
⋇ = Wilson
+ = Ramsay
mean diff. -0.59

Figure 4

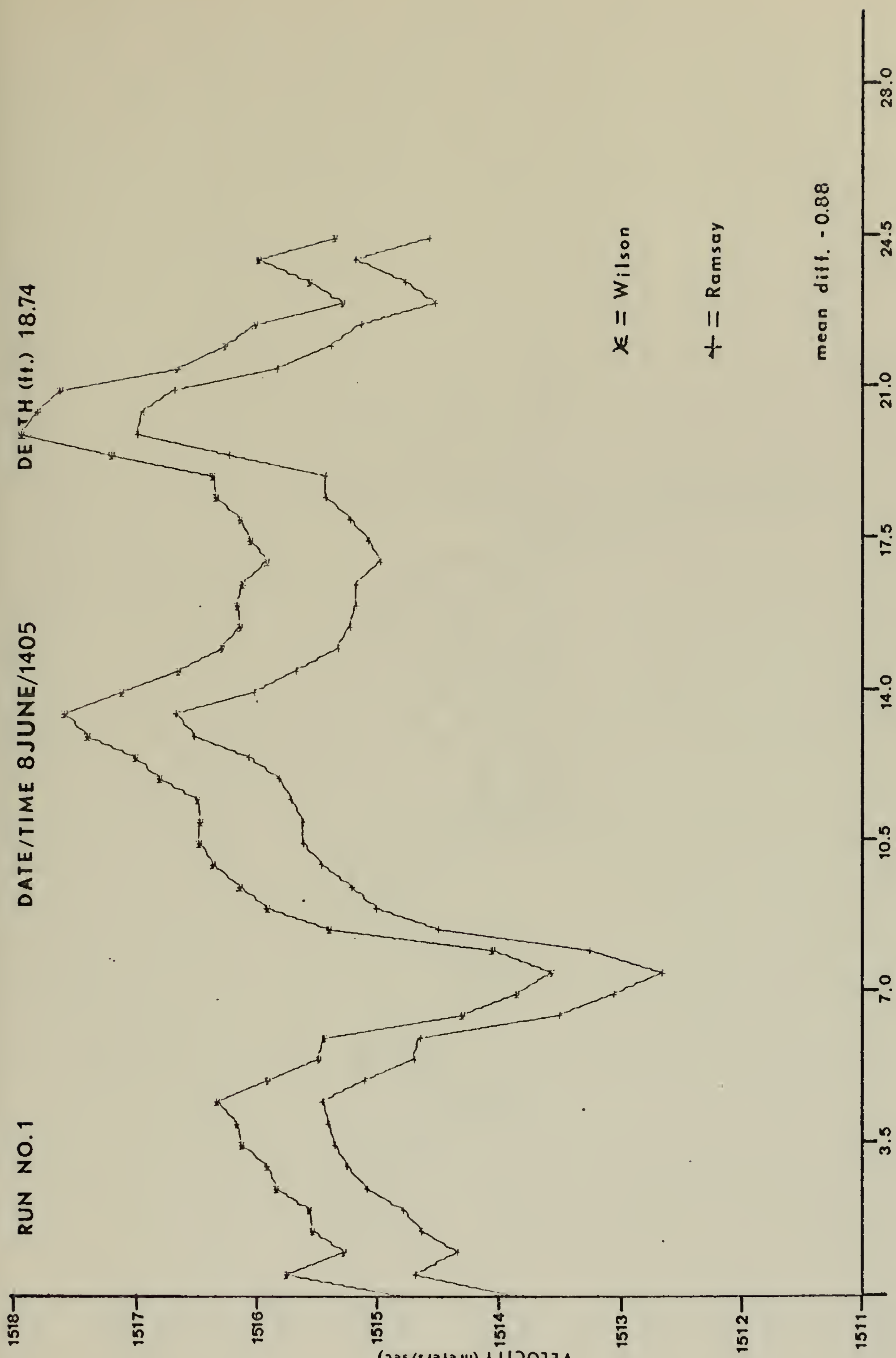
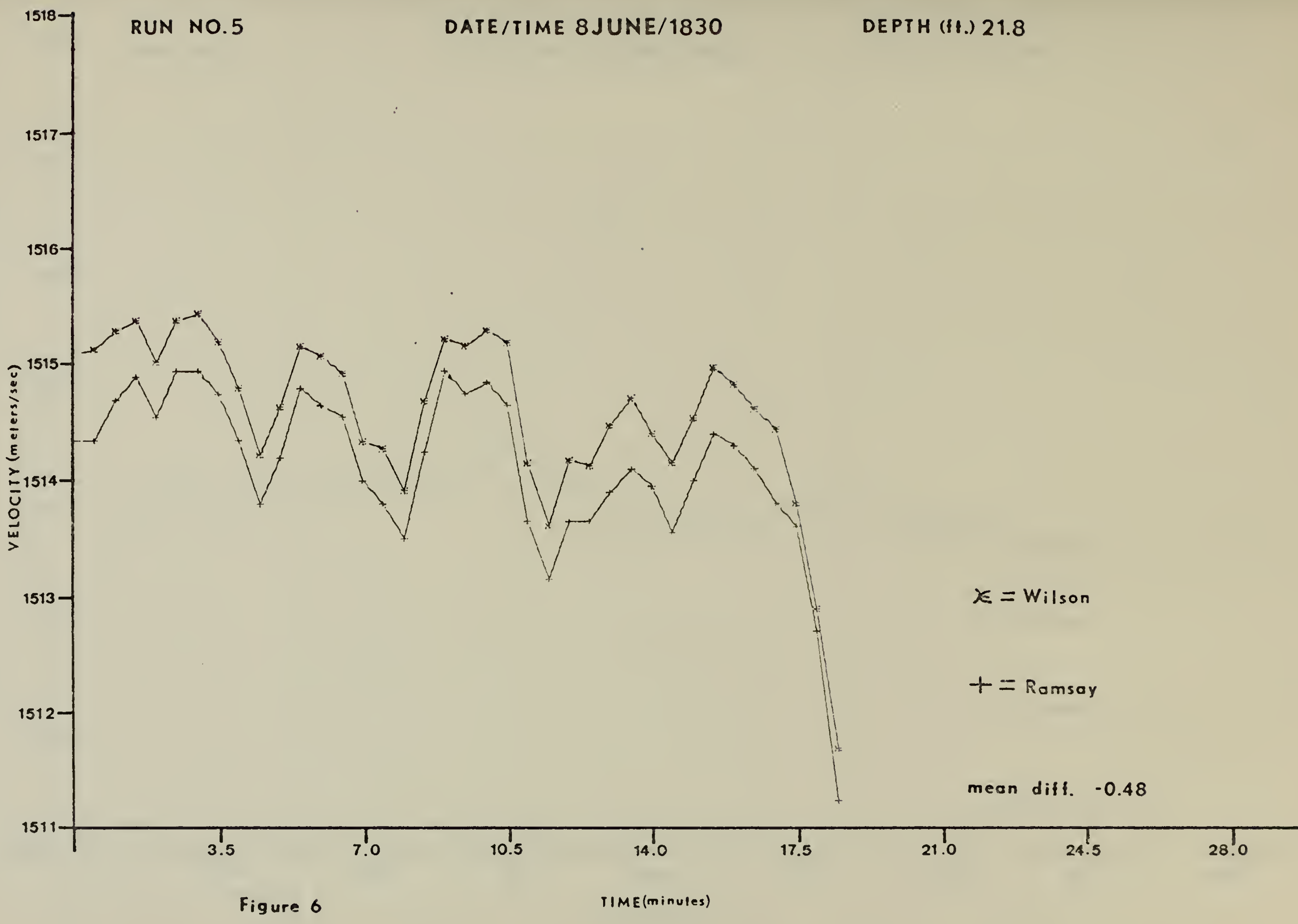

RUN NO.1
DATE/TIME 8JUNE/1405
DEPTH (ft.) 18.74
✕ = Wilson
+ = Ramsay
mean diff. -0.88
VELOCITY (meters/sec)
1518
1517
1516
1515
1514
1513
1512
1511
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME(minutes)

Figure 5



RUN NO.5
DATE/TIME 8JUNE/1830
DEPTH (ft.) 21.8
1518
1517
1516
1515
1514
1513
1512
1511
VELOCITY (meters/sec)
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME(minutes)
= Wilson
+ = Ramsay
mean diff. -0.48

Figure 6

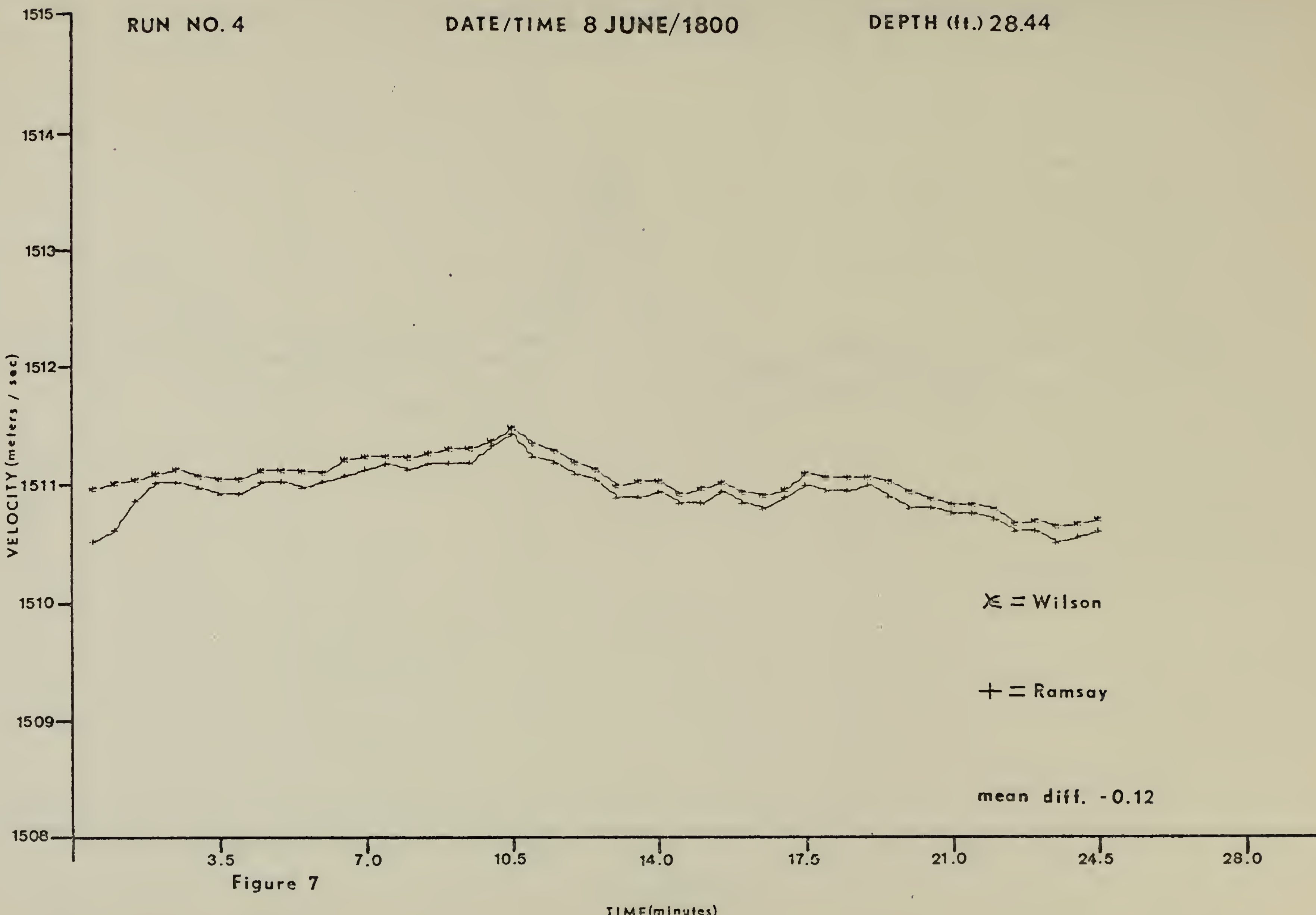
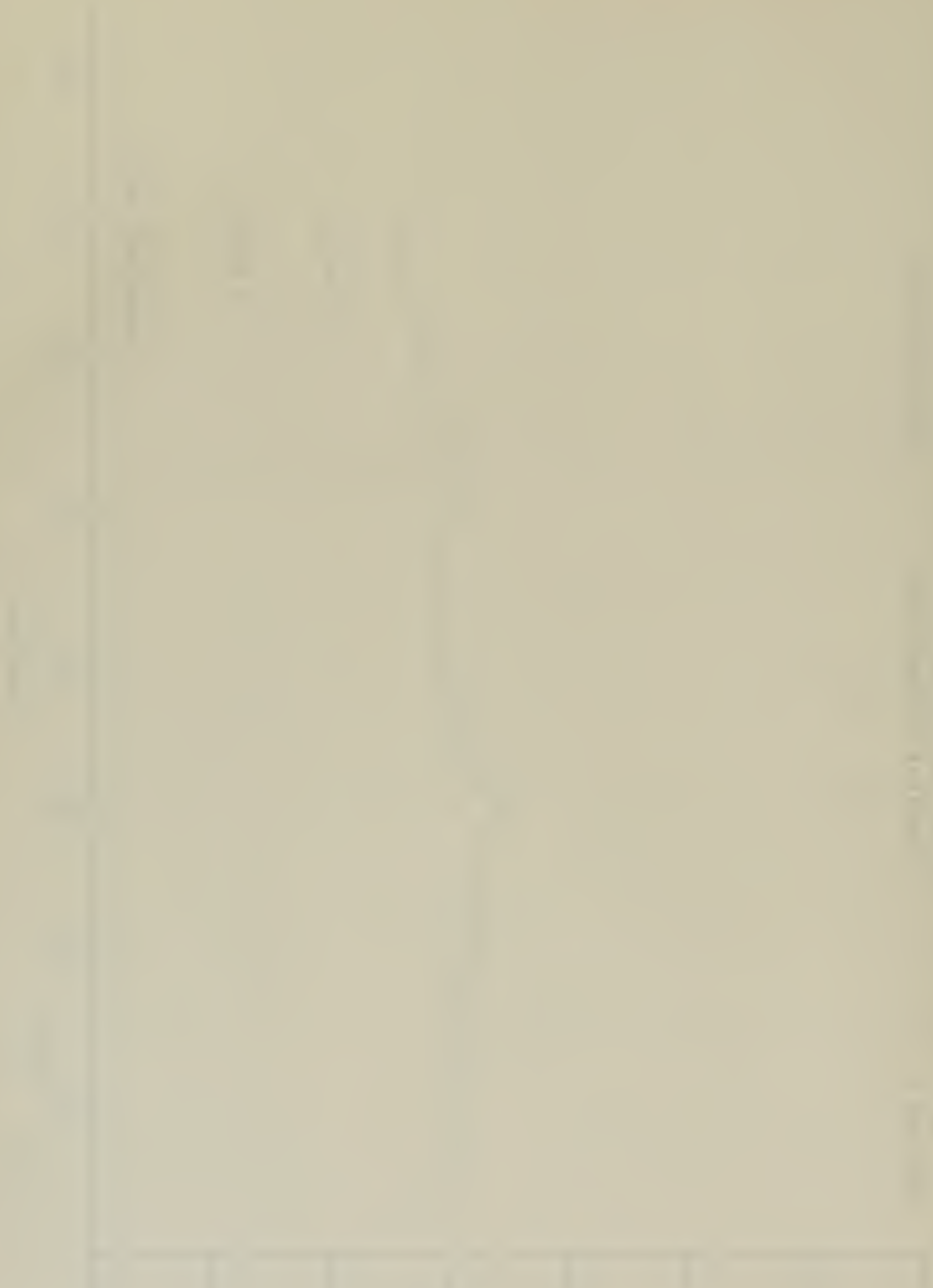

RUN NO. 4
DATE/TIME 8 JUNE/1800
DEPTH (ft.) 28.44
1515
1514
1513
1512
1511
1510
1509
1508
VELOCITY (meters / sec)
= Wilson
+ = Ramsay
mean diff. -0.12
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)

Figure 7



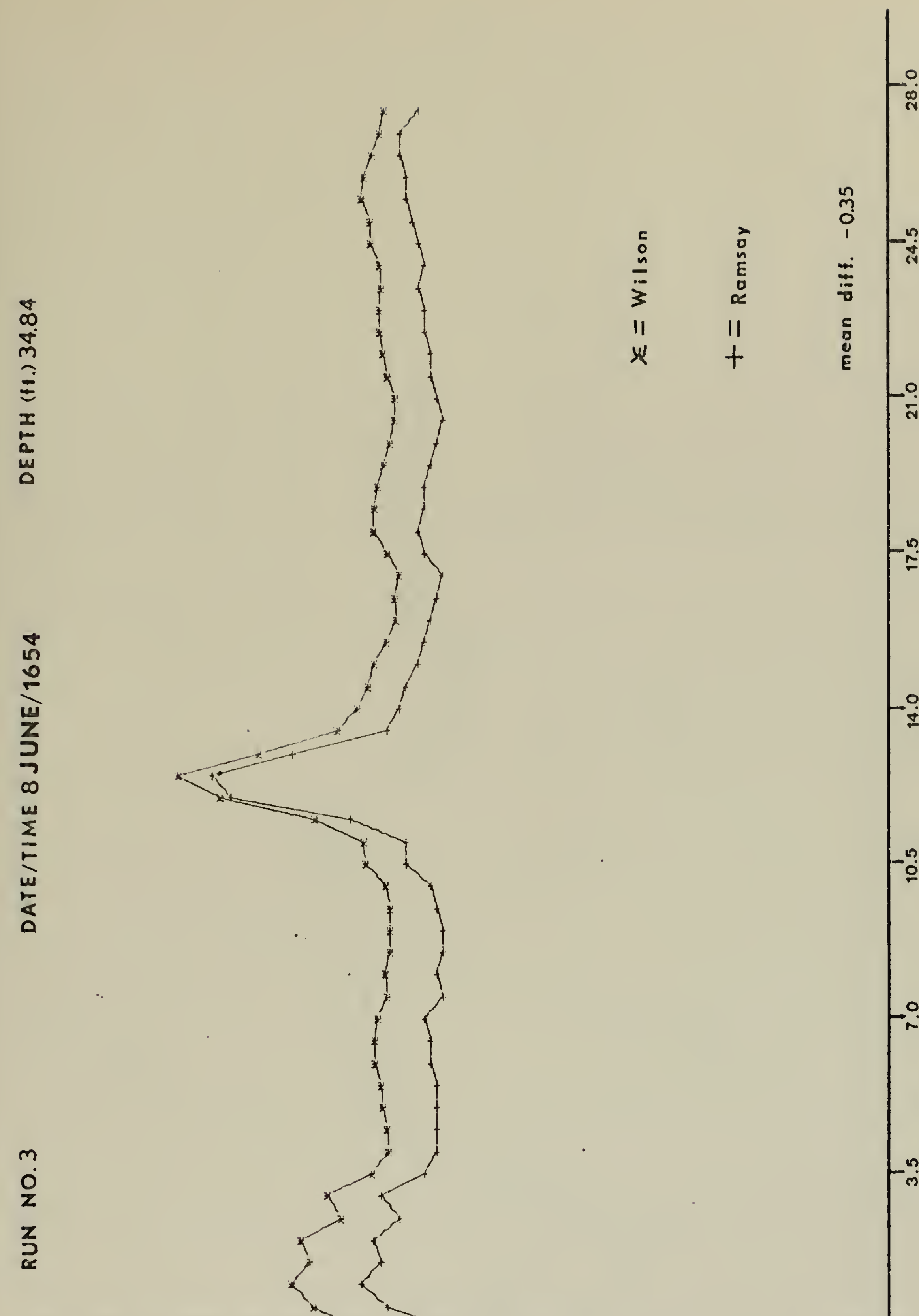

RUN NO. 3
DATE/TIME 8 JUNE/1654
DEPTH (ft.) 34.84
VELOCITY (meters / sec)
1515
1514
1513
1512
1511
1510
1509
1508
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)
✕ = Wilson
+ = Ramsay
mean diff. -0.35

Figure 8

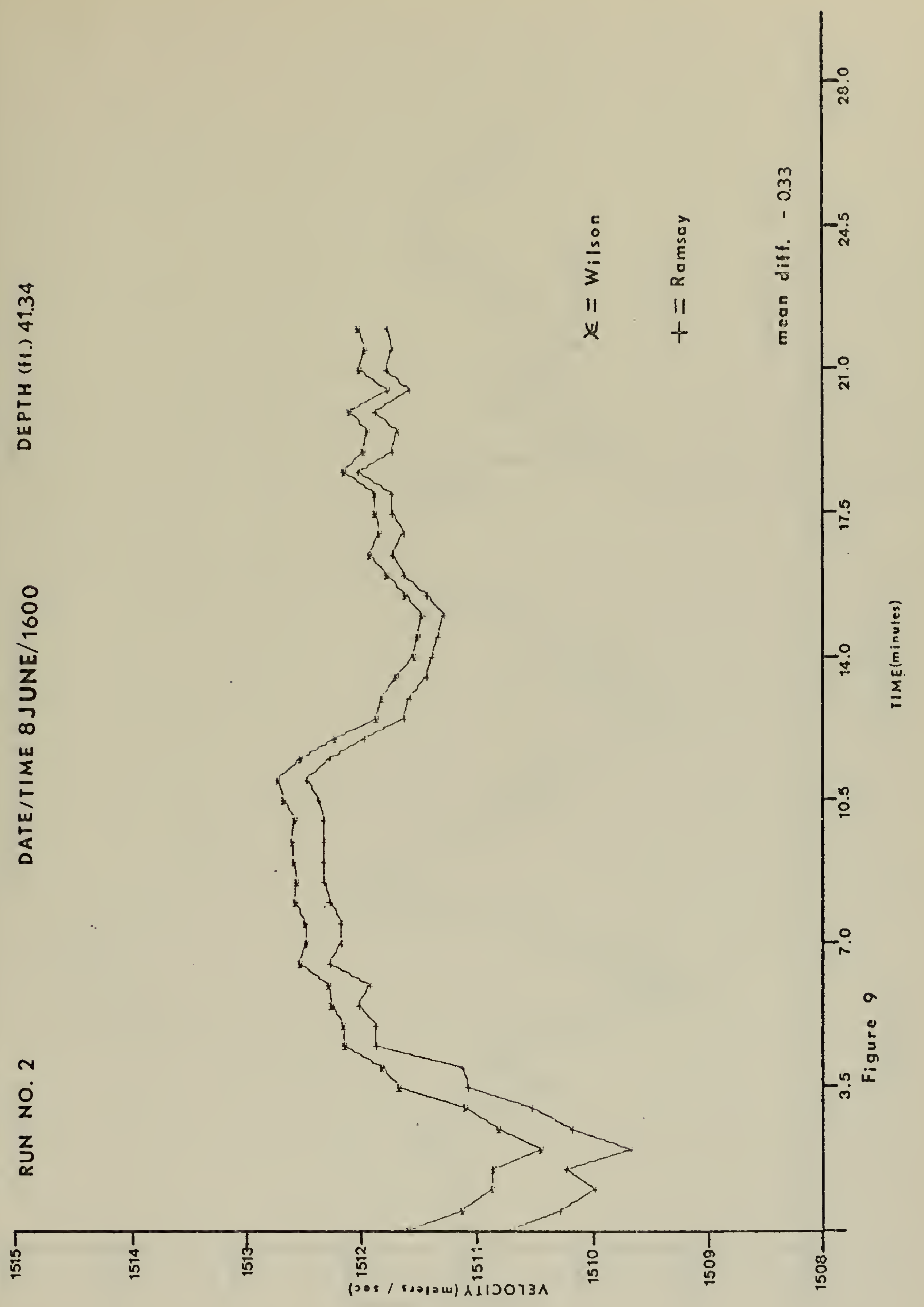

RUN NO. 2
DATE/TIME 8 JUNE/1600
DEPTH (ft.) 41.34
✕ = Wilson
+ = Ramsay
mean diff. - 0.33
VELOCITY (meters / sec)
1515
1514
1513
1512
1511
1510
1509
1508
TIME (minutes)
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0

Figure 9

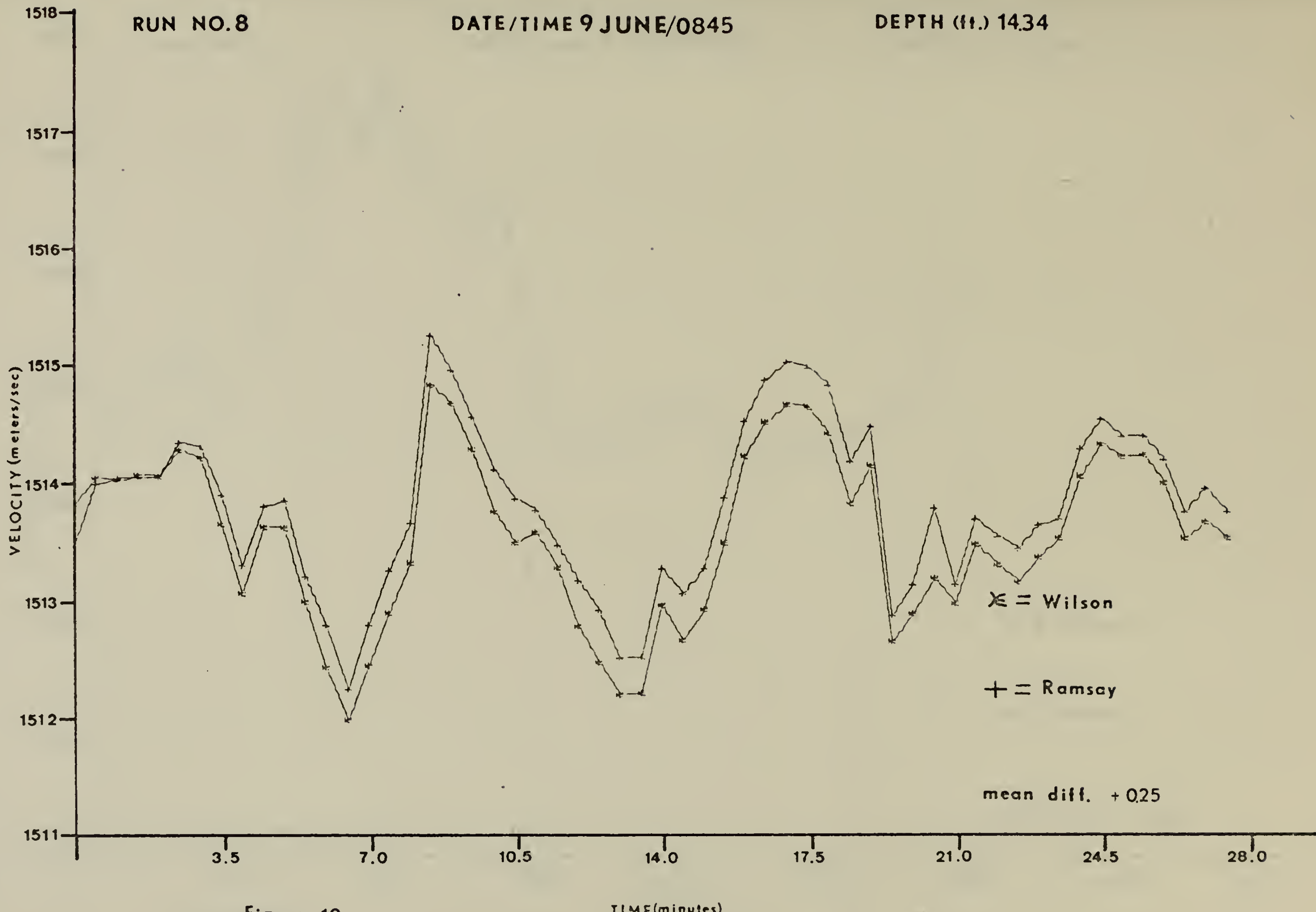
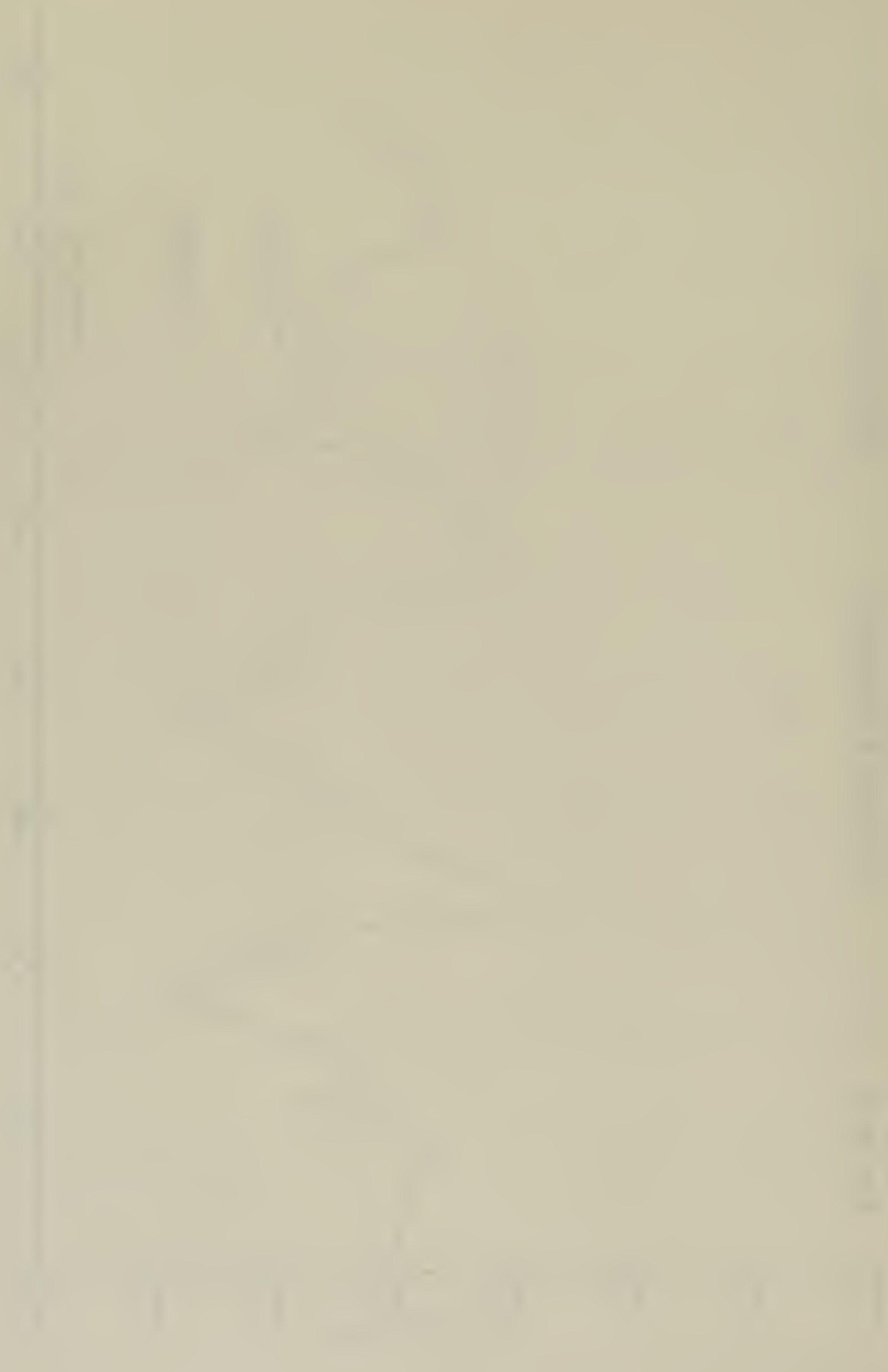

RUN NO.8
DATE/TIME 9 JUNE/0845
DEPTH (ft.) 14.34
1518
1517
1516
1515
1514
1513
1512
1511
VELOCITY (meters/sec)
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME(minutes)
✕ = Wilson
+ = Ramsay
mean diff. + 0.25

Figure 10



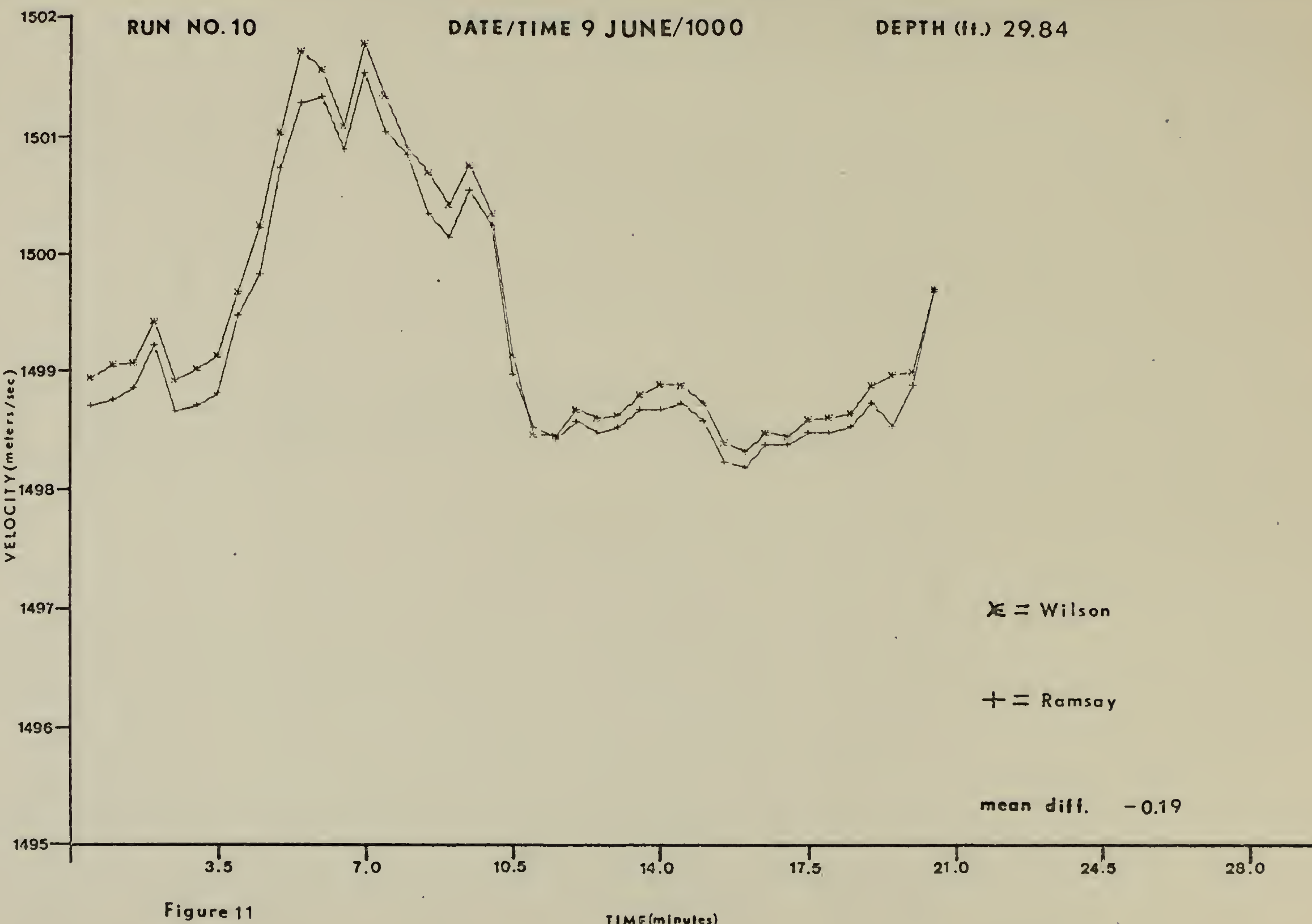
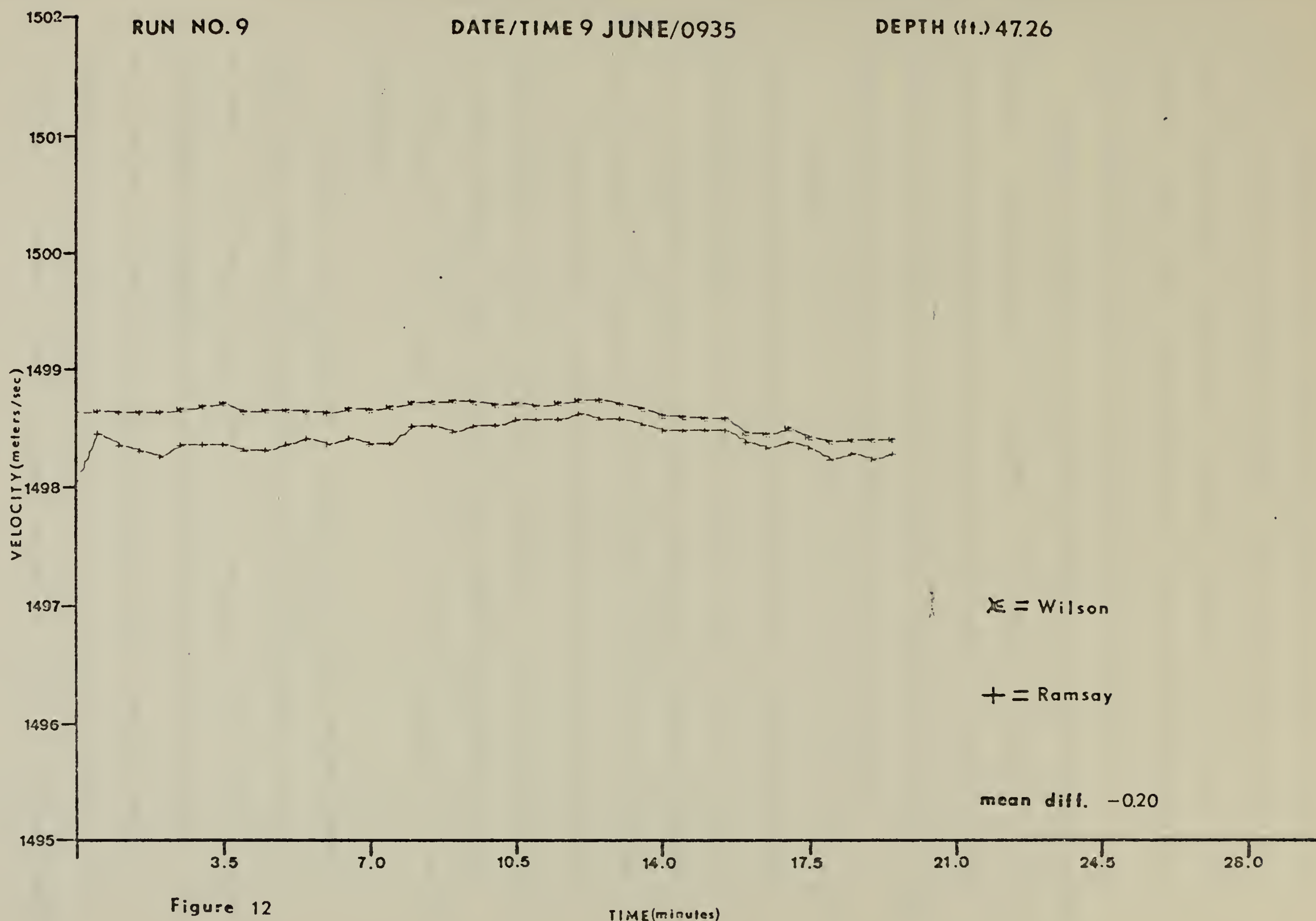

RUN NO. 10
DATE/TIME 9 JUNE/1000
DEPTH (ft.) 29.84
1502
1501
1500
1499
1498
1497
1496
1495
VELOCITY (meters/sec)
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)
⋇ = Wilson
+ = Ramsay
mean diff. -0.19

Figure 11



RUN NO. 9
DATE/TIME 9 JUNE/0935
DEPTH (ft.) 47.26
VELOCITY (meters/sec)
1502
1501
1500
1499
1498
1497
1496
1495
3.5
7.0
10.5
14.0
17.5
21.0
24.5
28.0
TIME (minutes)
✕ = Wilson
+ = Ramsay
mean diff. -0.20

Figure 12

A review of runs 8, 9 and 10 from the 9th of June in Figures 10 thru 12, shows some different results. Run 8 which was at the same depth as Run 6 from the previous day, has a difference not only within Wilson's evelope, but is also positive. At depths of about 28 feet and below, values come closer to those obtained the previous day.

Table IV summarizes the average differences of the measured sound velocity from the indicated equations. The standard deviation of differences are essentially the same for each equation on any given run. This points out that the empirical relations examined are basically the same at the near surface and are separated only by a constant.

It appears that Frye and Pugh's equation is more often closer to the actual values than Wilson's October equation. Even Wilson's June, 1960 equation appears to give better results overall than his October one. Del Grosso's equation had better results on 8 June as compared to any of the listed equations, but this did not hold true on 9 June.

Figures 13 and 14 graphically display these results for Wilson's October equation and Frye and Pugh's equation. Frye and Pugh indicated in their published report [3] that their standard deivation was only 0.1 m/sec. The outer limits are indicated for both equations on respective figures.

The most interesting part of these data is the contrast between Runs 6 and 8 which were essentially run at the same depth. In Run 6 we have a relatively large degradation of measured sound velocity from our standard, regardless of what equation we chose for a standard. In Run 8 we have an error on the positive side of our standard, which in Wilson's case is still within tolerance, but for Frye and Pugh is over 0.3 m/sec. in excess of this standard deviation. What in the environment

would cause such a sharp contrast? To assist in examining this aspect it was necessary to use the digitized data previously discussed. While it was not adequate to look at absolute values of sound velocity, it was quite sufficient for a spectral analysis approach. Additionally, environmental differences were reviewed. Besides the time of day being different with Run 6 in the evening hours and Run 8 in the morning, the bathytheromograph pointed to an entirely different thermal structure as shown in Figure 16 and 17. Figure 15 which shows the thermal structure for Run 5, is also examined because of it not only being available in digitized form, but its apparent transitional status between the two extremes in Runs 6 and 8. Run 1 was not examined in detail because of an apparent malfunction when converting from octagonal to hexadecimal on the IBM 360 computer.

The approach taken was to take each run in question and analyze sound velocity in conjunction with temperature, salinity, and waves to see how and to what degree each was related to sound velocity and how this relation varied. To do this the coherence was calculated for sound velocity and each of the above variables. The coherence was obtained by calculating the spectrum and cross-spectrum for both variables and solving

$$\text{Coherence (f)} = \frac{Q^2(f) + C_o^{\,2}(f)}{S_x(f)\ S_y(f)}$$

where Q = Quadrature estimate of frequency f

C_o = Cospectrum

S_x = Spectrum estimate of variable y

S_y = Spectrum estimate of variable x

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TABLE IV

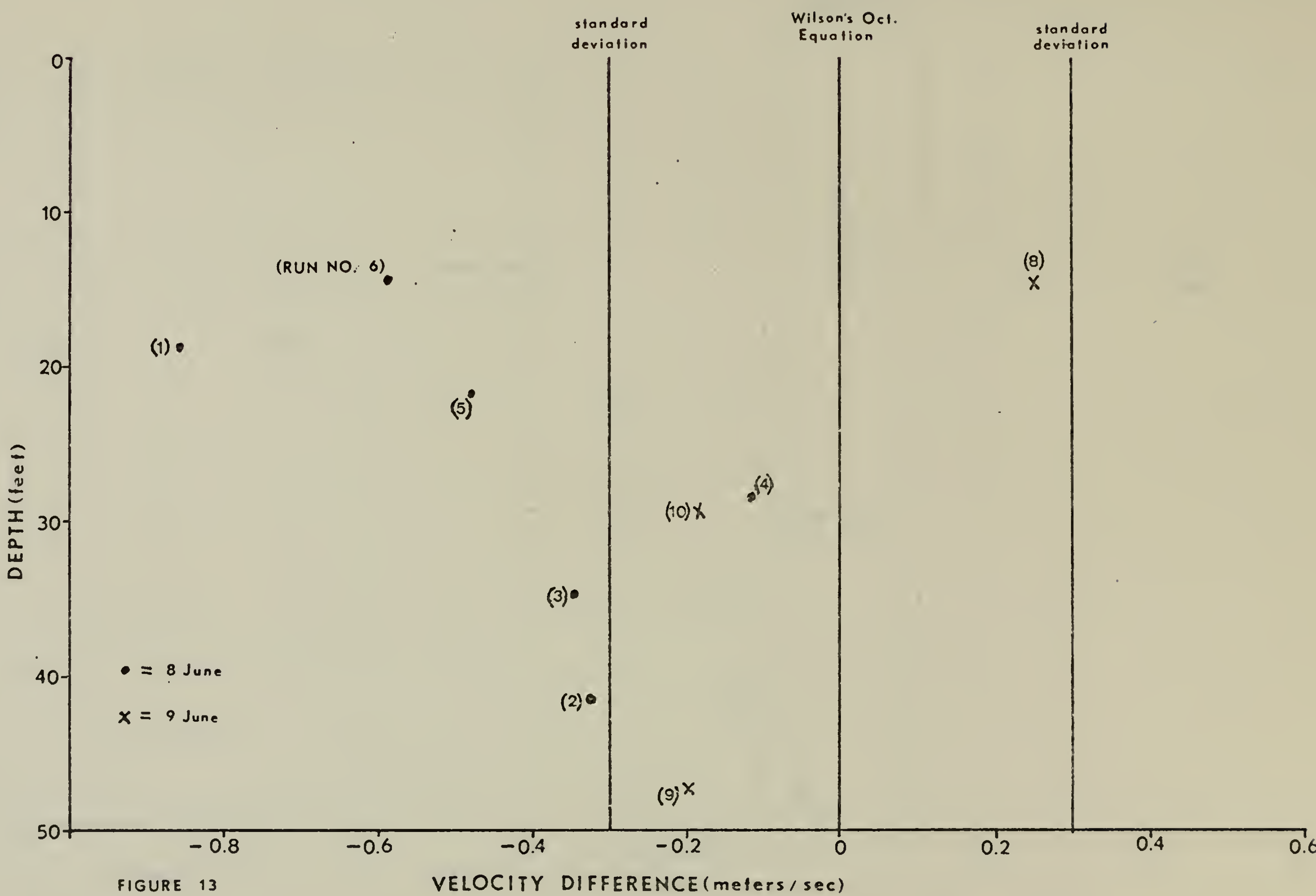
8 JUNE, 1972

RUN	WILSON JUNE '60	STD	WILSON OCT. '60	STD	DEL GROSSO(4)	STD	FRYE & PUGH	STD	DEPTH(ft.)
6	-0.50	.16	-0.59	.15	-0.33	.15	-0.38	.16	14.34
1	-0.83	.09	-0.88	.09	-0.68	.09	-0.71	.09	18.74
5	-0.39	.13	-0.48	.12	-0.26	.12	-0.27	.14	21.80
4	-0.02	.07	-0.12	.07	-0.16	.07	-0.09	.07	28.44
3	-0.25	.11	-0.35	.11	-0.09	.12	-0.14	.11	34.84
2	-0.23	.21	-0.33	.21	-0.07	.21	-0.12	.21	41.34

9 JUNE, 1972

RUN	WILSON JUNE '60	STD	WILSON OCT. '60	STD	DEL GROSSO(4)	STD	FRYE & PUGH	STD	DEPTH(ft.)
8	0.32	.15	0.25	.14	0.49	.14	0.44	.14	14.34
10	-0.09	.11	-0.19	.11	0.22	.12	-0.03	.11	29.84
9	-0.11	.11	-0.20	.11	0.21	.10	-0.06	.10	47.26

(STD = Standard Deviation)
(Values are in meters/second)



standard deviation
Wilson's Oct. Equation
standard deviation
0
10
20
30
40
50
DEPTH (feet)
(RUN NO. 6)
(1)
(5)
(3)
(2)
(10)
(4)
(9)
(8)
● = 8 June
X = 9 June
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
VELOCITY DIFFERENCE (meters / sec)

FIGURE 13

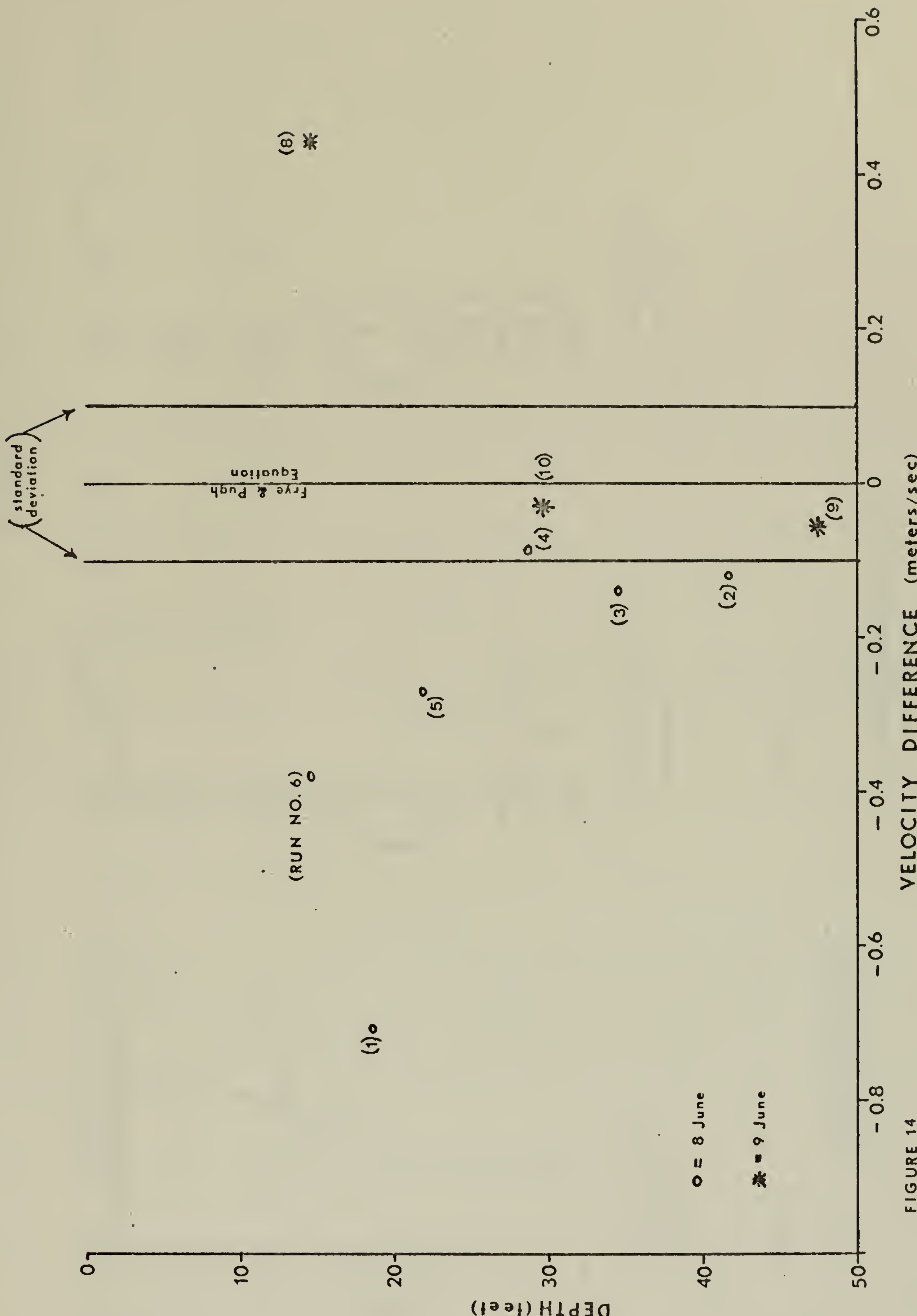
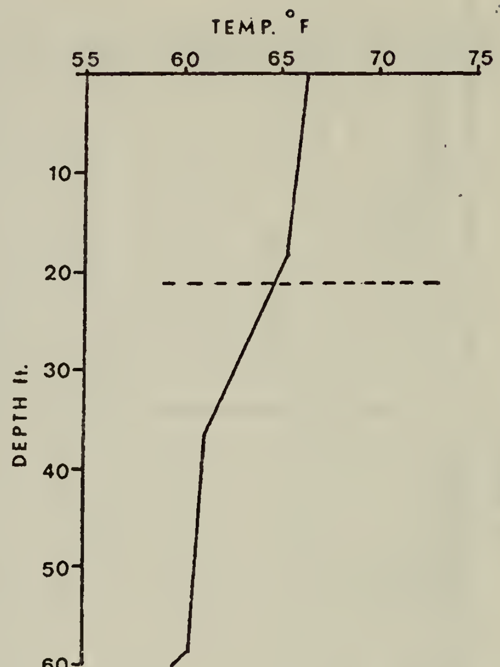
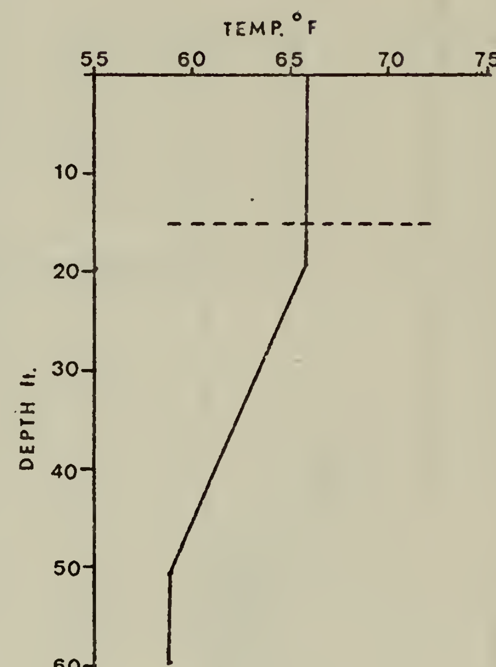

standard deviation
Frye & Pugh Equation
(RUN NO. 6)
(1)
(2)
(3)
(4)
(5)
(8)
(9)
(10)
o = 8 June
* = 9 June
DEPTH (feet)
0
10
20
30
40
50
VELOCITY DIFFERENCE (meters/sec)
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6

FIGURE 14



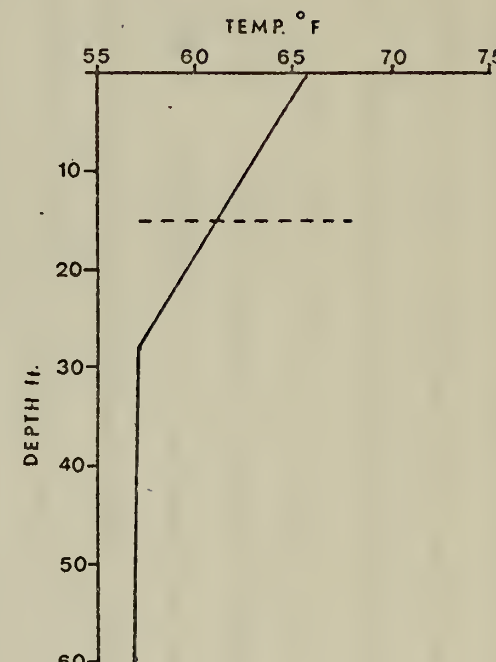
RUN 5, 8 JUNE
TIME: 1830

Figure 15



RUN 6, 8 JUNE
TIME: 1935

Figure 16



RUN 8, 9 JUNE
TIME: 0905

Figure 17

- - - - - - - - - - - Indicates position bottom of frame

BATHYTHERMOGRAPHS

A. SOUND VELOCITY AND TEMPERATURE

As expected there was good coherence between temperature and sound velocity on all runs. However, this relationship was by no means constant. Figures 18, 19 and 20 show coherence values plotted out to 0.6 Hz or 1.6 second period. There is a significant change in coherence from runs 5 thru 8. The increase in overall coherence, proceeding from runs 6, 5 and 8, corresponds to an increase from negative to positive values in the sound velocity differences shown in Figures 13, 14 and Table IV. To establish a means of putting a number on the change of coherence, we can take from each graph that frequency where the coherence first goes below a value of one-half (Table V). The band width of coherence has increased by almost a factor of two.

TABLE V

RUN	FREQ. AT WHICH COHERENCE OF TEMP. & SOUND VELOCITY FIRST GOES BELOW 0.5
6	.13
5	.18
8	.24

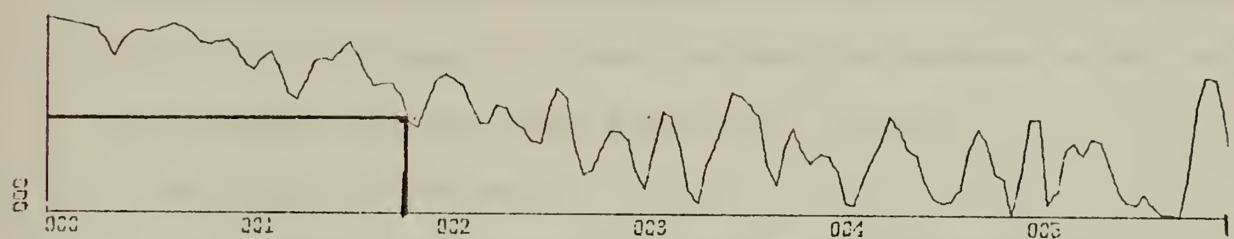
TABLE VI

FREQ.	COHERENCE VALUES: TEMP. VS. S.V.* RUNS 6	5	8	S.V.* VS. WAVES RUNS 6	5	8	TEMP. VS. WAVES RUNS 6	5	8
.04	.74	.87	.84	.01	.06	.04	.02	.05	.02
.05	.85	.93	.87	.31	.15	.11	.28	.16	.06
.06	.91	.94	.94	.59	.45	.56	.64	.48	.48
.07	.82	.95	.95	.31	.51	.75	.41	.55	.80
.08	.77	.87	.87	.10	.42	.60	.18	.45	.64

* Sound Velocity

X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 6 SV AND TEMP

Figure 18



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 5 SV AND TEMP

Figure 19

X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 8 SV AND TEMP

Figure 20

What this means is that the relationship between temperature and sound is not constant, and that the variation depends also on other environmental influences. Going back to the BT's for these runs we see in Run 6 the situation is essentially isothermal, and in Run 8 there is a sharp gradient which suggests little mixing. There is also observed a peak value for all runs at about .06 Hz which was the average frequency of the swell. If Figures 18 thru 20 are overlain, there is observed a general agreement of peaks and valleys throughout the frequency range with these growing in size corresponding to an increase in difference of sound velocity value from a negative to positive value. The bandwidth in the vicinity of swell frequency for very high coherence values (above 0.8) is broader for Runs 5 and 8 than that of Run 6.

B. SOUND VELOCITY AND WAVES

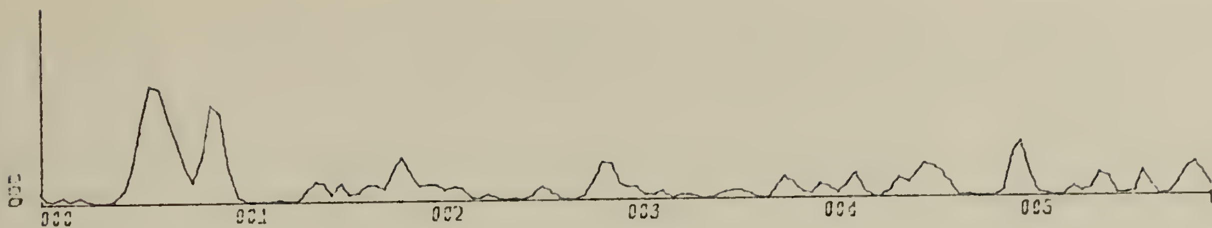
The coherence of sound velocity and waves show high values in the vicinity of the swells for all runs, but again as with coherence of sound and temperature, the bandwidth or overall area of high coherence in the area of swells increases as sound velocity difference increases from the negative to positive values. Figures 21 thru 23 are coherence curves of sound and waves.

C. TEMPERATURE AND WAVES

Coherence of temperature with waves shows essentially the same picture as sound and waves. The increasing bandwidth of high values from Runs 5 thru 8 is very noticeable. Figures 24 thru 26 are the coherence curves for temperature and waves.

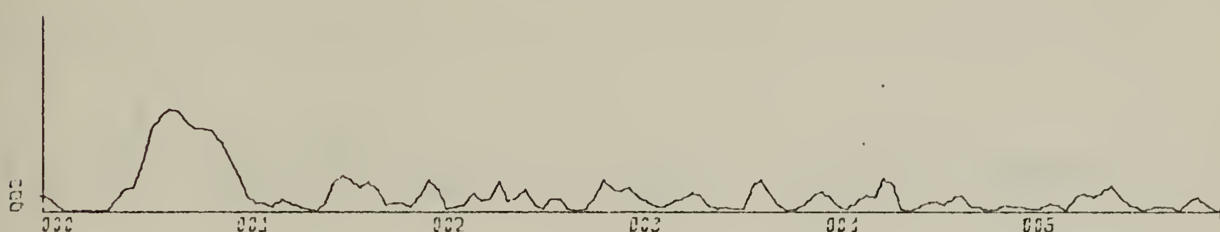
These coherence curves seem to suggest that:

(a) when isothermal conditions exist near the surface the apparent relation between sound velocity and temperature seems to deteriorate.



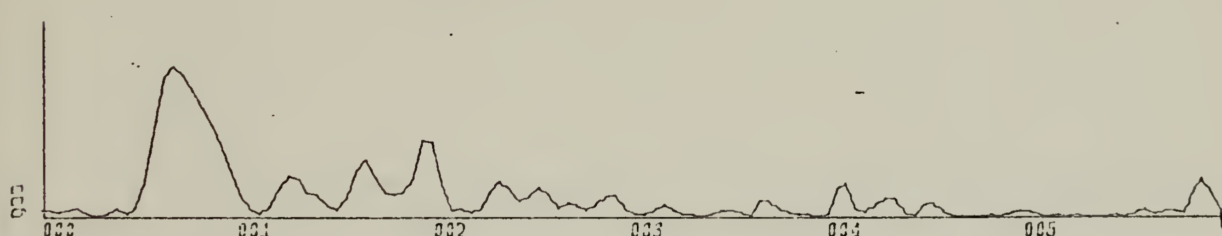
X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 6 SV AND WAVES

Figure 21



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 5 SV AND WAVES

Figure 22

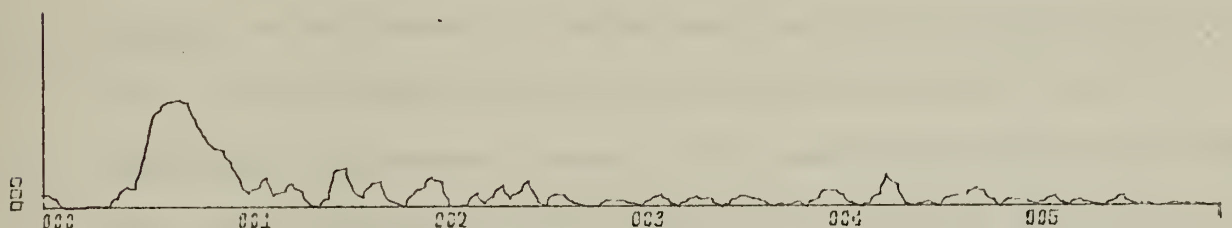


X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 8 SV AND WAVES

Figure 23

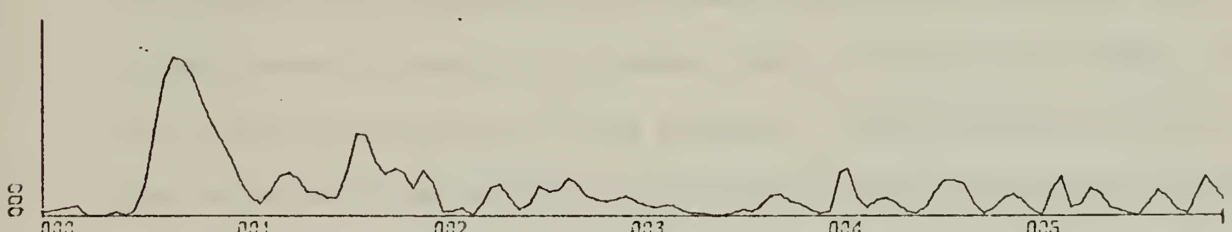
X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 6 TEMP AND WAVES

Figure 24



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 5 TEMP AND WAVES

Figure 25



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
CØHERENCE RUN 8 TEMP AND WAVES

Figure 26

(b) when strong gradients are restored the apparent relation of temperature and sound velocity is restored.

A review of the enviornment shows that the near surface isothermal conditions were probably brought about by winds which were up to 8 and 10 kts. during the day. In the evening the wind drops off, sun sets, and the heat loss during the night combined with little wind produces a strong stable gradient.

Why does an isothermal condition at the near surface effect the relation between sound and temperature? This seems to be our critical question at this point. It is believed that what we observe occurring here is not so much a change in relation between sound velocity and temperature, but rather a change in the mean thermal patch size. Therefore, the difference of sound velocity from a standard established by any of the empirical values is a function of this patch size, and diameter of the sound path. Under isothermal conditions such as experienced in this experiment, the mixing, caused primarily by the wind, breaks the patches into very small size, perhaps, less than 8 cm, which is the approximate width or diameter of the sing around. When the wind drops off patches sort themselves out to their equilibrium depth creating larger patches. There is, of course, heat loss during the night, but low winds allow retention of the gradient. Measuring sound velocity such as in Run 8, we can see by the strong positive difference as well as the BT that there is very little mixing and patches at a given depth are probably of good size.

Unfortunately, the only way this could be proved would be to have a series of temperatures properly spaced along with a velocimeter and then choosing a standard velocity equation calculate sound differences.

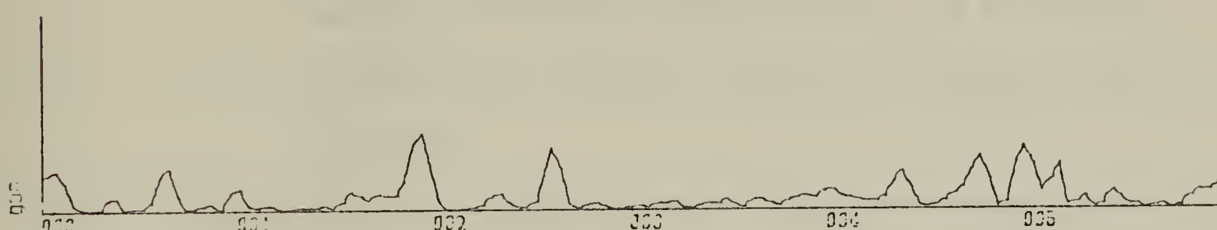
Patch size would be calculated using the autocorrelation function as discussed by Lieberman [16]. It is believed that with sufficient differences obtained with use of a computer and carefully controlled potentiometers a high coherence would be observed between patch size and sound velocity difference. Assuming that a relation between sound velocity difference and patch size exists it appears that it is a function of the depth that wind mixing is felt, which in this experiment is down to about 20 ft. A mixing parameter, therefore, based on a relation of patch size is perhaps an appropriate addition to a standard equation if a more precise mean sound speed is desired. Table VI summarizes the coherence values discussed, with high coherence values at about the frequency of the predominate swell.

D. SOUND VELOCITY AND SALINITY

The coherence of sound velocity and salinity was examined and while there is a degree of coherence at the wave period it is neither strong nor does its value change significantly from one run to another. This would indicate the weak influence of salinity on sound velocity as well as the basically isohaline condition at this location off San Diego. Figures 27 thru 29 contain the coherence curves of sound velocity and salinity.

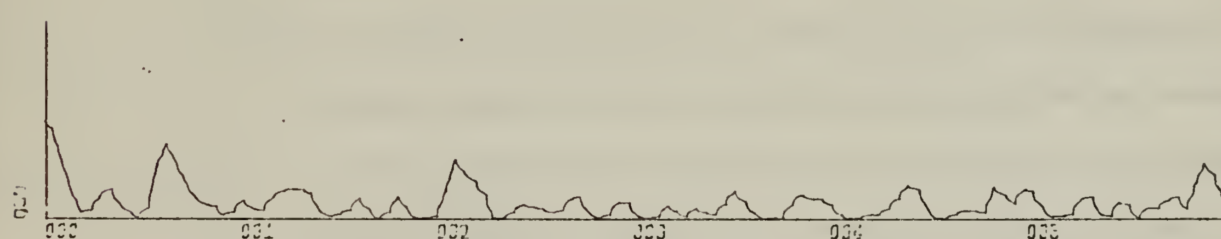
X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
COHERENCE RUN 6 SV AND SALINITY

Figure 27



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
COHERENCE RUN 5 SV AND SALINITY

Figure 28



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
COHERENCE RUN 8 SV AND SALINITY

Figure 29

VII. OBSERVATIONS AND CONCLUSIONS

The observations made from this comparison and study of the sound velocity differences are:

(a) The Frye and Pugh equation was the more precise formula under most circumstances of the several empirical formulae examined.

(b) Ideally, for operational purposes, a better sound velocity for solving range problems would be one averaged for a period of 20 minutes both vertically and horizontally. However, it is realized that this is currently not practical.

(c) Errors in calculated sound speed were maximum under isothermal conditions at the near surface (0 to 20 ft.) and a negative correction of about 0.5 m/sec. applied to Frye and Pugh's equation produced a velocity closer to actual sound velocity. A negative correction of 0.7 m/sec. applied to Wilson's October equation accomplished the same.

(d) A possible explanation for relatively larger differences between measured and calculated sound speed at the surface is that turbulence induced by the wind produces very small thermal patches, which on the average reduce the speed of sound moving through them. The difference between measured and calculated sound speed is therefore a function of the thermal patch size and length of the sound path of the velocimeter.

In future experiments it is recommended that an effort be made to measure temperatures at intervals ranging from 1 cm to about 60 cm on an X, Y, Z axis if possible for purposes of calculating patch sizes.

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13. ABSTRACT

Measured values of sound velocity in sea water are compared to sound velocity calculated by several empirical relations. Among the empirical relations examined are Wilson's October, 1960 equation and Frye and Pugh's 1971 equation. Results indicate that all empirical relations have their maximum differences in the first 20 feet of sea water. The difference measured is dependent on wind induced turbulence. Of the empirical relations examined, the Frye and Pugh equation provides the most accurate results.

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